TANDEM AND CROSS COMPOUND TURBINE BASED LOAD FREQUENCY CONTROL OF MULTI AREA POWER SYSTEM WITH SSSC AND REDOX UNIT

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Abstract—The design of load frequency control system plays important role in automation of power system. This paper proposes a sophisticated application of Redox flow batteries (RFB) coordinated with Static Synchronous Series Compensator. In the present work, an attempt has been made to understand the dynamic performance of Automatic Generation Control (AGC) of multi area thermal-thermal power system and hydro-thermal power system with tandem and cross turbines. Non-linearities like generation rate constraint and governor dead band is also considered. During large load disturbance in the areas, conventional controllers alone are incapable of reducing frequency deviations and tie-line power oscillations due to the slow response of the speed governor mechanism. Hence to improve the dynamic response of load frequency control, redox flow batteries are added to both the areas due to their quick response and lower time constant. Ziegler Nichols method is used to tune the PI controllers. Simulation studies reveals that the effectiveness of the SSSC and RFB, especially in terms of overshoots, under shoots and settling time, thereby improving the performance of LFC in the deregulated power system.

Keywords—Load Frequency Control (LFC), Automatic Generation Control (AGC), Static Synchronous Series Compensator(SSSC), Redox Flow Battery(RFB), Governor Dead Band (GDB), Generation Rate Constraint (GRC).

I. INTRODUCTION

Electric power generation and consumption should perfectly go in hand if an electric energy system is to be stringently maintained in its nominal state characterized by nominal frequency, voltage profile and load flow configuration. But because of the random nature of the power demands, the power generation consumption at equilibrium, cannot be strictly met in reality, thus the power deviation occurs. Since system conditions are always changing as load constantly varies during different hours of a day, precise manual control of these balances would be impossible [5]. LFC is developed to maintain a constant frequency and to regulate the tie line flows. To get an accurate insight into the AGC problem, it is necessary to include the important physical constraints in the system model. The major physical constraints that influence the power system performance are GRC and GDB. All governors in the power system have dead bands like mechanical friction, backlash, valve overlaps in hydraulic relays, which are important for speed control even under small disturbances, so the speed governor dead band has denoting effect as the dynamic performance of LFC system.

In a power system another most important constraint on modern large size thermal units is the stringent generation rate constraint (i.e.), the power generation can change only at a specified maximum rate [21]. The GRC of the system is considered by adding a limiter to the control system. The improvement of turbine efficiency is extremely important subject from the viewpoint of demand to reduce exhausted CO$_2$ and consumption of fossil fuel. In order to improve thermal efficiency, higher pressure and higher temperature steam conditions are gaining attention. Fast acting energy storage device Super Conducting Magnetic Energy Storage (SMES) is incorporated in the system which effectively damp out power frequency and tie line power oscillations caused by small load disturbances. The most advantage of SMES is that the time delay during charge and discharge is quite short [17].
Power is available almost spontaneously and very high power output can be provided for a brief period of time. However, the disadvantage of SMES is the high capital cost of the cooling units.

To overcome this problem, a high speed response compensator should be used. The recent advances in power electronics have led to the development of the FACTS. These FACTS devices are capable of controlling the network condition in a very fast manner and because of this reason the usage of facts devices are more apt to improve the stability of power system [12,14]. The series part known as static synchronous series compensator can be controlled without restrictions. It is necessary to include battery ion energy storage system especially in the present deregulated scenario to improve the automatic generation control problems. There are several types of battery energy storage systems used in power system application such as lead acid batteries, flooded type batteries, valve regulated (VRLA) type batteries, sodium sulphur (NaS) batteries, Lithium ion (Li ion), Metal air and Redox flow batteries (RFB).

Among all batteries RFB are promising for the applications which require high power and long duration storage. RFB is an active power source which can be essential not only as a fast energy compensation device for power consumptions of large loads, but also as a stabilizer of frequency oscillations [10,15]. The RFB will in addition to load compensating, can have other applications such as power quality maintenance for decentralized power supplies. The simulation result shows the effectiveness of the SSSC and RFB, especially in terms of overshoots, undershoots and settling time, thereby improving the performance of LFC in deregulated power system.

II. SYSTEM INVESTIGATED

A. System Model

The transfer function model of two area reheat thermal power system with single tandem compound reheat turbine, boiler dynamics and SMES is shown in fig.1. The system is also incorporated with governor dead band and generation rate constraint. Matlab version 2017 has been used to obtain dynamic response of change in frequencies $\Delta f_1$, $\Delta f_2$ and $\Delta P_{tie}$ for 1% step load perturbation. Proper assumptions and approximations made to linearize the mathematical equations which describe the system and transfer function model. The system has been designed for nominal system frequency.
### B. Boiler Dynamics

Boiler is a device for producing steam under pressure. Figure 2 shows the model to represent the boiler dynamics. Basically, this model is drum type boiler. An oil/gas fired boiler system has been considered in this study, because such boilers respond to load demand changes more quickly than coal fired units. Drum type boiler is otherwise known as recirculation boilers which rely on natural or forced circulation of drum liquid to absorb energy from the hot furnace walls, called water walls for generating steam [13]. The boiler receives feed water which has been preheated in the economizer and provides saturated steam outflow. Recirculation boiler make use of a drum to separate steam flow from the recirculation water so that it can proceed to the super heater as a heatable vapour, hence, recirculation boiler are referred to as drum type boiler. For boiler control strategies or modes of operation, there are four methods available, namely, boiler leading, turbine leading, coordinated boiler turbine control and sliding pressure control, here, boiler leading or turbine following mode of control is considered. With this operation, the MW demand signal is applied to combustion controls. Steam flow and MW output closely follow steam production in the boiler. Boiler following controller tends to be fairly response to AGC signals, on the order of 3% min $G_1$ for a 30% excursion particularly if fueled by oil or gas. The AGC signal usually drives the speed-load set point adjusts on the speed-governor control action which in turn, causes turbine valve movement. The boiler control senses the changes in stem pressure to adjust flows of air, fuel etc.

![Fig.2 Boiler Dynamics](image)

### C. Governor Dead Band

Governor dead band is defined as the total magnitude of a sustained speed change within which there is no resulting change in valve position. Mechanical friction and valve over laps in hydraulic relays are the sources of governor [20]. As a consequence of this, even though the input signal increases, the speed governor may not immediately respond until the input reaches the particular value. Similarly when the input signal decreases, the output does not follow it but remains constant till it decreases to certain value. Dead band introduces non-linearity in the system model and has the effect of broadening the speed governor regulation. The presence of dead band makes the system more oscillatory.

### D. Generation Rate Constraint

In practical steam turbine system, due to thermodynamic and mechanical constraint, there is a limit to the rate at which its output power can be changed. This limit is referred to as generation rate constraint. The main reason to consider GRC is that the rapid power increase would draw out excessive steam from the boiler system to cause steam condensation due to adiabatic expansion. The condensation of steam may produce minute water drops to abrade the turbine blade by hitting. The steam valve of the high pressure (HP) turbine acts as a control valve associated with the LFC. Since the temperature and pressure in the HP turbine are normally very high with some margin, it is expected steam condensation would not occur with about 20% stem flow change unless the boiler stem pressure itself does not drop below a certain level. The long time abrasion of the turbine blader due to minute water drops can be serious problem while short time abrasion given little effects as the turbine blader.

![Fig.3 Generation Rate Constraint](image)
The boiler can afford to keep its steam pressure to be constant for a while, and thus it is possible to increase power generation up to certain limit of normal power during the first tens of seconds. Generation rate constraint block diagram is shown in the fig.3. After the generation has reached this marginal upper bound the power increase of the turbine should be restricted by the GRC.

E. Tie Line

A multi area interconnection is comprised of region, or areas, that are interconnected by tie-line. Tie-lines have the benefit of providing inter area support for abnormal conditions as overall as the transmission parts for contractual energy exchange between the areas. System interconnection leads to increase in reliability of electric supply. In the event of one utility falling short of generation, due to forced outage of generators an unexpected increase in demand, another utility of the pool can come to its rescue by making its surplus power available [25].

![Fig.4 Frequency Tie-line Characteristics](image)

Depending on whether one or all the system have been assigned the job of maintaining the frequency constant and extent of tie line load required, three methods are available for LFC of interconnected system, known as flat frequency control, flat tie line load control and tie line load bias control. The main disadvantage of flat frequency control is that it results in random variations in tie line power.

The aim of flat tie line load control is to keep the tie line power constant irrespective of load demands. This control is used when a small system and a large system are interconnected through a tie line. The large system maintains the system frequency and small system is controlled to keep the tie line power constant. The main disadvantage is that, it is not suitable when two or more large system are interconnected because in such cases the tie line power and frequency deviation have a tendency to swing back and forth following a load change.

Tie line load bias control is the most widely used method on large interconnections. Frequency tie line load relationship is shown in fig.4. The control signals are proportional to the change in frequency as well as change in tie line power.

\[
ACE_A = \Delta P_{AB} + \alpha_A \Delta f_A
\]

(1)

Where,
- \( ACE_A \) = Area control error of system A
- \( \Delta P_{AB} \) = Change in power transfer from A to B
- \( \alpha_A \) = Frequency bias constant
- \( \Delta f_A \) = Frequency change in system A

Most of the time a control area is interconnected with many other areas through several tie lines. Let there be a total of m tie lines. Then for the \( i^{th} \) control area, the net interchange is the sum of power transfer over all the m tie lines. The area control
error $ACE_i$ of the $i^{th}$ area should be proportional to total exchange of power can be expressed as,

$$ACE_i = \sum_{j=1}^{m} \Delta P_{ij} + \alpha_i \Delta I_i$$

(2)

### III. TANDEM AND COMPOUND TURBINE

A steam turbine derives its source from the boiler of a nuclear reactor or fossil fuels furnaces and its converts the high pressured steam into rotating energy at high temperature which in turn is converted into electrical energy. Building of steam turbines always rests upon the unit size and steam conditions. Turbines have a set of moving blades called rotors or buckets and stationary blades called vanes or nozzle sections [3]. Through these nozzles steam is accelerated with high velocity and this steam is converted to shaft torque by the buckets. Usually turbines are with multiple sections. They may be either tandem compound or cross compound turbine.

A. Tandem Compound Turbine

One shaft would hold all the sections and with single generator. Mostly used now-a-days as it is not that expensive compared to cross compound. Fig. 5 & 6 shows the block diagram of tandem single and tandem double compound turbine [19].

B. Cross Compound Turbine

It has two shafts connected to two separate generators and it is being run by one or more turbine sections. Still it is considered to be as one unit and controlled with one of controls. It is obvious that cross compound improves efficiency and increase the capacity. Fig. 7 & 8 shows the block diagram of cross single and cross double compound turbine.
IV. CONVENTIONAL CONTROLLER

The controller is an impedance bridge which is at the balance when the frequency is 50 Hz. When the frequency varies (by a small value as 0.005 Hz) an unbalance current flows, the direction of current depending on whether the change in the frequency is positive or negative. The steady state frequency can be adjusted to the desired value by adjusting the speed changer setting of the governor.

In this paper dynamic performance of automatic load frequency control of two area power system is done by using PI controller. Ziegler Nichols method is used to optimize the gain values of PI controller. The proportional term produces an output value that is proportional to the current error value [16]. The proportional response can be adjusted by multiplying the error by a constant $K_p$, called the proportional gain constant [23,24]. The proportional term is given as follows,

$$ P_{out} = K_p e(t) \tag{3} $$

The contribution from the integral term is proportional to both the magnitude of the error and the duration of the error. It is expressed as follows,

$$ I_{out} = K_i \int_0^t e(\tau) \, d\tau \tag{4} $$

The Ziegler Nichols tuning method is a heuristic method of tuning a PID controller. It was developed by John.G.Ziegler and Nathaniel.B.Nichols. The Ki and Kd gains are first set to zero. The proportional gain is increased until it reaches the ultimate gain $K_u$, at which the output of the loop starts to oscillate. $K_u$ and the oscillation period $T_u$ are used to set the gain. Formula to calculate the gain value is shown in table I.

<table>
<thead>
<tr>
<th>TABLE I. ZIEGLER NICHOLS METHOD</th>
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<tr>
<td>Control type</td>
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<td>P</td>
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V. SUPER CONDUCTING MAGNETIC ENERGY STORAGE

Many kinds of stabilizers have been proposed to improve the stability of a synchronous generator. The super conducting magnetic energy storage (SMES) is designed to store electric energy in the low loss super conducting coil. Power can be absorbed or released from the coil according to the system requirement [18,22]. The control is performed by changing the firing angle of the converters in the SMES unit, which rapidly moves the D.C output voltage up or down in order to achieve the desired power interchange. The gate turn off (GTO) converters makes it possible for the SMES unit to operate in four quadrant modes. However the effective use of the SMES unit greatly depends on its control strategy. Fast acting energy storage device, SMES can effectively damp out power frequency and tie line power oscillations caused by small load disturbances.

VI. STATIC SYNCHRONOUS SERIES COMPENSATOR

Figure.11 shows the two-area interconnected power system with a configuration of SSSC used for the proposed control design. It is assumed that a large load with rapid step load change has been experienced by area1. This load change causes serious frequency oscillations in the system. Under this situation, the governors in an area 1 cannot sufficiently provide adequate frequency control. On the other hand, the area 2 has large control capability enough to spare for other area. Therefore, an area 2 offers a service of frequency stabilization to area 1 using the SSSC. Since SSSC is a series connected device, the power flow control effect is independent of an installed location. In the proposed design method, the SSSC controller uses the frequency deviation of area 1 a local signal input [1,2]. Therefore the SSSC is placed at the point near area1. Moreover the SSSC is utilized as the energy transfer device from area 2 to area1. As the frequency fluctuation in area 1 occurs, the SSSC will provide the dynamic control of the tie-line power by exploiting the system interconnections as the control channels and the frequency oscillation can be stabilized [4].

A. Mathematical Model of SSSC

In this study, the mathematical model of the SSSC for stabilization of frequency oscillations is derived from the characteristics of power flow control by SSSC [1]. By adjusting the output voltage of SSSC ($V_{SSSC}$) the tie-line power flow ($P_{12}+jQ_{12}$), can be directly controlled. Since the SSSC fundamentally controls only the reactive power, then the phasor $V_{SSSC}$ is perpendicular to the phasor of line current $I$, which can be expressed as

$$\bar{I} = \bar{V}_1 - \bar{V}_2 - jV_{SSSC}I/X_1$$  \hspace{4cm} (5)

Where $X_1$ is the reactance of the tie-line, $\bar{V}_1$ and $\bar{V}_2$ are the bus voltages at bus 1 and 2 respectively. The active power and reactive power flows through bus 1 are,

$$P_{12}+jQ_{12} = V_I*$$  \hspace{4cm} (6)

where $\bar{I}$ is conjugate of $\bar{I}$. Substituting $\bar{I}$ from eq (5) and eq (6)

$$P_{12}+jQ_{12} = [(V_1V_2/X) \sin(\delta_1-\delta_2)] - (V_{SSSC} V_1 \bar{I}^*/X_1 I) + j ((V_1^2/X_1)- (V_1V_2/X_1) \cos(\delta_1-\delta_2))$$  \hspace{4cm} (7)

Where,

$$V_1 = V_1 e^{j\delta_1} \text{ and } V_2 = V_2 e^{j\delta_2}$$

From eq (6) and (7) gives,

$$P_{12} = ((V_1V_2/X_1) \sin(\delta_1-\delta_2)) - ((P_{12}/X_1) V_{SSSC})$$  \hspace{4cm} (8)

The second term of right hand side of eq (8) is the active power controlled by SSSC. Here, it is assumed that $V_1$ and $V_2$ are constant, and the initial value of $V_{SSSC}$ is zero. i.e., $V_{SSSC}=0$. By linearizing (7) about an initial operating point,

$$\Delta P_{12} = ((V_1V_2 \cos(\delta_1-\delta_2))/X_1) (\Delta \delta_1 \Delta \delta_2) - (P_{12}/X_1L) \Delta V_{SSSC}$$  \hspace{4cm} (9)

Where subscript “o” denotes the value at the initial operating point by varying the SSSC can be controlled as
\[ \Delta P_{\text{SSSC}} = \left[ \frac{P_{12} \text{ o}}{X_1} \right] V_{\text{SSSC}} \]  

(10)

In eq (9) implies that the SSSC is capable of controlling the active power independently. In this study, the SSSC is represented by the power flow controller where the control effect of active power by SSSC is expressed by \( \Delta P_{\text{SSSC}} \) instead of \( \left[ \frac{P_{12} \text{ o}}{X_1} \right] V_{\text{SSSC}} \). Eq (9) also can be represented as

\[ \Delta P_{12} = \Delta P_{T12} + \Delta P_{\text{SSSC}} \]  

(11)

Where,

\[ \Delta P_{T12} = \left( \frac{V_1 V_2 \cos (\delta_{1o} - \delta_{2o})}{X_1} \right) (\Delta \delta_1 - \Delta \delta_2) \]

\[ \Delta P_{T12} = T_{12} (\Delta \delta_1 - \Delta \delta_2) \]  

(12)

Where \( T_{12} \) is the synchronizing power coefficient.

VII. REDOX FLOW BATTERY

The configuration of Redox Flow Battery is shown in figure 9. A sulfuric acid solution containing vanadium ions is used as the positive and negative electrolytes, which are stored in respective tanks and circulated to battery cell [9]. The Redox Flow Batteries offer the following features, and are suitable for high capacity systems that differ from conventional power storage batteries. The battery reaction only involves a change in the valence of a vanadium ion in the electrolyte. There are none of the factors which reduce the battery service life seen in other batteries that use a solid active substance, such as loss are electro depositions of the active substance [6,11].

Furthermore, operations at normal temperatures ensure less deterioration of the battery materials due to temperature. Pumps and piping that are widely used in facilities such as chemical plants are usable as established technologies. The system configurations are such that battery output (cell section) and battery capacity (tank section) can be separated, therefore the layout of the sections can be altered according to the place of installation. For example, the tank can be placed underground. The design can be easily modified according to the required output and capacity. The charged electrolyte is stored in separate positive and negative tanks when the battery has been charged, therefore no self-discharge occurs during prolonged stoppage nor is auxiliary power required during stoppage [7,8]. Furthermore, start-up after prolonged stoppage requires only starting of the pump, thus making start-up possible in only a few minutes. The electrolyte (i.e., the active substance) is sent to the each battery cell from the same tank, therefore the charging state of each battery cell is the same, eliminating the need for special operation such as uniform charging. So that, maintenance is also easy because the electrolyte is relatively safe and the operating are at normal temperature and assures superior environmental safety. Waste vanadium from generating stations can be used so it can be superior recyclability. Furthermore, the vanadium in the electrolyte can be used semi-permanently.
The RFB systems are incorporated in the power system to suppress the load frequency control problem and to ensure an improved power quality. In particular, these are essential for reusable energy generation units, such as wind power and photovoltaic generator units, which need measures for absorption of changes in output and to control flicker and momentary voltage drop. With the excellent short-time overload output and response characteristics possessed by RFB in particular, the effects of generation control and of the absorption of power fluctuation needed for power quality maintenance are expected. The set value of the RFB has to be restored at the earliest, after a load disturbance so that the RFB unit is ready to act for the next load disturbance. The RFB are capable of very fast response and therefore, hunting due to a delay in response does not occur. Fig. 10 shows simplified block diagram of RFB.

\[
\frac{\Delta P_{RFI}}{\Delta P_{RFO}} = \frac{K_{RF}}{1 + sT_D}
\]

Fig. 10 Simplified Transfer Function Model of RFB

Fig. 11 Transfer Function Model of Two Area Hydro Thermal Power System for Proposed Magnetic Storage Unit

The various simulation results for the proposed block diagram are shown below.
Fig. 12 Tandem single turbine thermal area 1

Fig. 13 Tandem single turbine thermal area 2

Fig. 14 Tandem single turbine thermal tie-line

Fig. 15 Tandem double turbine thermal area 1

Fig. 16 Tandem double turbine thermal area 2

Fig. 17 Tandem double turbine thermal tie-line
Fig. 18 Cross single turbine thermal area 1

Fig. 19 Cross single turbine thermal area 2

Fig. 20 Cross single turbine thermal tie-line

Fig. 21 Cross double turbine thermal area 1
Fig. 22 Cross double turbine thermal area 2

Fig. 23 Cross double turbine thermal tie-line

Fig. 24 Tandem single turbine hydrothermal area 1

Fig. 25 Tandem single turbine hydrothermal area 2
Fig. 26 Tandem single turbine hydrothermal tie-line

Fig. 27 Tandem double turbine hydrothermal area 1

Fig. 28 Tandem double turbine hydrothermal area 2

Fig. 29 Tandem double turbine hydrothermal tie-line
Fig. 30 Tandem double turbine hydrothermal area 1

Fig. 31 Tandem double turbine hydrothermal area 2

Fig. 32 Tandem double turbine hydrothermal tie-line

Fig. 33 Cross double hydrothermal area 1
Fig. 34 Cross double hydrothermal area 2

Fig. 35 Tandem_cross single turbine governor position

Fig. 36 Tandem_cross single mechanical power
Fig. 37 Tandem_cross single speed

Fig. 38 Tandem_cross double turbine governor position

Fig. 38 Tandem_cross double mechanical power

Fig. 38 Tandem_cross double turbine speed
Finally, the simulation results conclude that redox units yield better performance than SMES and SSSC. The use of redox flow batteries (RFB) is evidenced to contribute significantly to the efficiency of overall generation control through their ability to quickly respond to changes. Due to the nature of RFB, extremely fast response is obtained. The RFB unit has a reduced charging and discharging period.

In an area under frequency deviations and tie-line power deviations, the redox flow batteries (RFB) are capable of consuming the oscillations of electromechanical modes in a power system. Because they provide storage capacity in addition to the kinetic energy of the stator, they contribute to the oscillation damping effect.

SMES, SSSC, and redox flow batteries units are compared. The compound turbine shows better performance than the reheat and tandem compound turbine. The SMES is used effectively to damp electromechanical oscillations in a power system, providing storage capacity in addition to the kinetic energy of the stator.

The redox flow batteries (RFB) are shown to be effective in load leveling and ensuring that the LFC capacity is restored after overload characteristics and quick response responsiveness. From this, it is evident that the RFB contributes a lot to promoting the efficiency of overall generation control through the effect of oscillation damping in multi-area interconnected power systems. For an overload condition, the RFB unit shows a reduced charging and discharging period.

References


